Satellite Constellations for Ka Band Communication

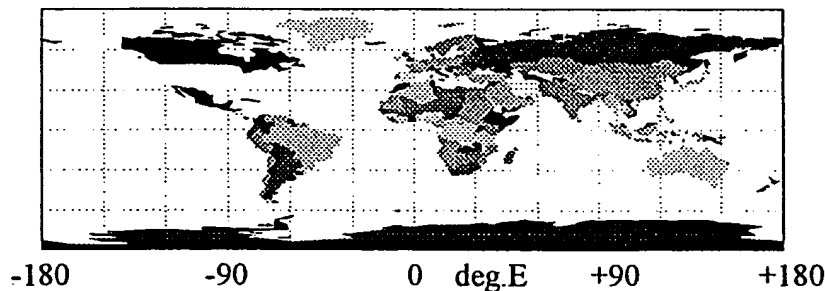Paul Christopher
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Abstract- Ka band performance is compared for GEO, Teledesic, and MolniyaGEO constellations in the Temperate Zone. MolniyaGEO is also found attractive at 40-46 GHz and 90 GHz throughout much of the Temperate Zone.
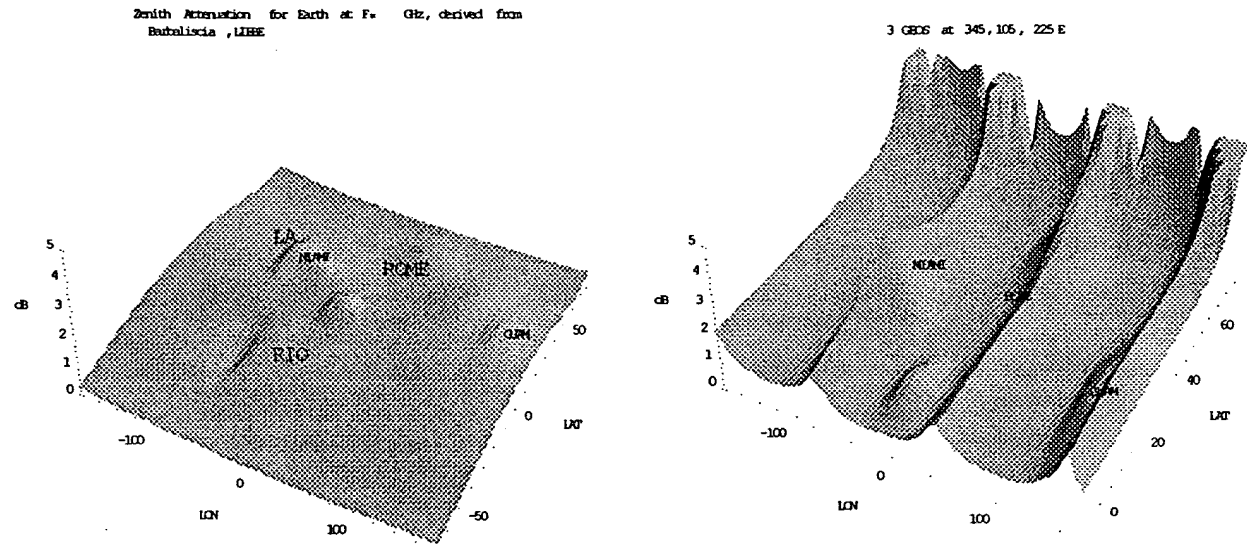
1.0 Background

Geostationary satellites have performed key communication tests for Ka band communication. However, they offer low elevation angles and high Ka band propagation loss for ground stations at high latitudes. This paper shows alternatives to GEOs and their advantages for Ka band. Exhaustive elevation angle studies are done for Teledesic and Molniya constellations. The elevation probability density functions (pdfs) are generated at each latitude for each constellation. The pdfs are then applied to worldwide zenith attenuation maps, as shown by Barbaliscia, Boumis, and Martellucci[1] and later generalized to other frequencies[2]. New attenuation maps appropriate to the constellations are shown. Higher frequencies are then examined. Frequencies in the 40-48 GHz and 90-100 GHz regions are shown to be attractive in the temperate regions for the non-GEO constellations.

F. Barbaliscia and the group at Foundation Ugo Bordone have allowed conceptual breakthroughs at frequencies greater than 40 GHz. First, they recognized that many VSAT applications function very well with only 95 to 99% availability. Then, they generated worldwide zenith attenuation maps for 99% nonrainy conditions at 49.5 and 22 GHz and other frequencies. Further examination of these maps showed that the maps could be approximately solved for water vapor and cloud attenuation. After the effects of clouds and water vapor were separated[2], zenith attenuation could be estimated over a wide range of frequencies with integrated gaseous attenuation models[3,4,5]. General zenith attenuation functions were found and one form was included with the 1999 Taormina paper[2]. A longer, more exact equation using Liebe's water vapor relations is used here to give slightly less attenuation than the short form at 90- 100 GHz. The long equation is too long to be included here, but is included in a current summary of advances in millimeter wave communication[6].

Fig.1-1 Coordinates for Barbaliscia's Attenuation Maps

Fig 1-1 shows the coordinate system chosen for Barbaliscia's worldwide zenith attenuation maps. The general attenuation of (2), which is useful for frequencies from 5 to 100 GHz, is used for the 30 GHz zenith attenuation of Fig. 1-2. Note Rome at the center top and Guam at the right margin. The zenith attenuation looks vaguely like the 'Face on Mars' with the west coast of South America as the right eye, Rome near the left cheekbone, and Guam on the double chin. Miami appears as a raised left eyebrow. The entire tropical region has raised attenuation with the exception of the West Coast of South America.

Fig. 1-2 Nonrainy Zenith Attenuation(30GHz)   Fig. 2-1GEO Att'n at 345,105,225E

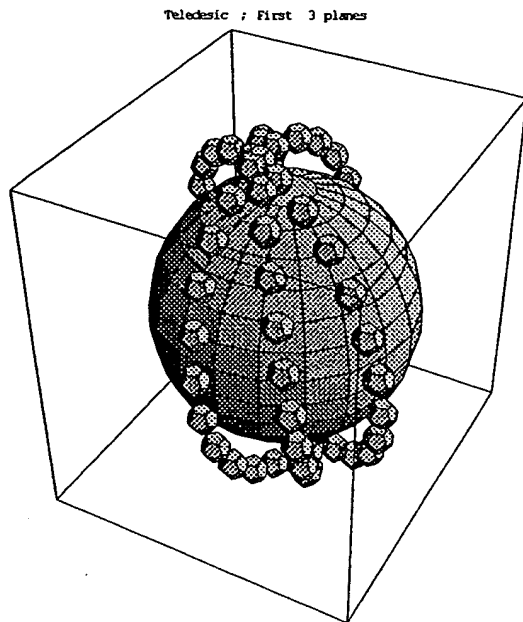## 2. Worldwide Attenuation for Geostationary Satellites

The low zenith attenuation of Fig.1-2 would occur only if satellites appeared directly overhead of the ground stations at all times. A few rare ground stations on the equator would enjoy the low zenith attenuation to GEOs, but attenuation for a general ground station would be weighted by the cosecant of elevation angle. Very long atmospheric paths and high attenuation would occur for latitudes higher than 70^0. Ground stations at latitudes greater than 81^0 would be simply out of luck

A typical GEO system might consist of satellites stationed at 345E, 105E, and 225E. Worldwide elevation angles may be calculated, the zenith attenuation weighted by the cosecant(elevation), and a GEO attenuation map generated as Fig. 2-1. (This map represents only the Northern Hemisphere to save space).
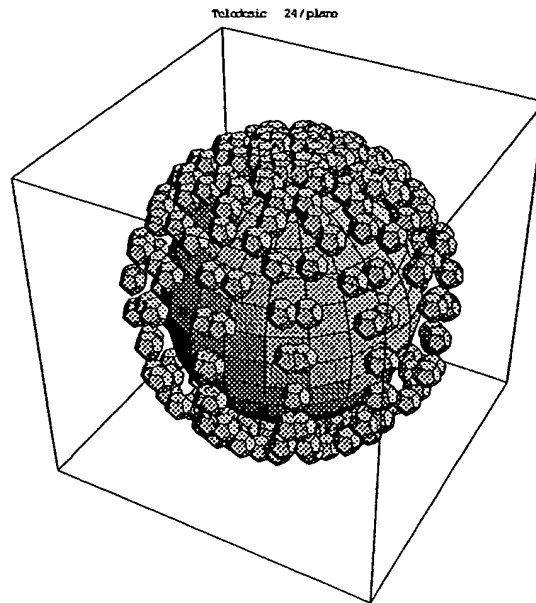
The middle satellite bridges the Atlantic well, with marginal attenuation to Miami and Rome. High latitudes such as Oslo(near 60N) would suffer badly however. We should emphasize that high latitudes between 60 to 70N are very important great circle routes for both aircraft and communication. Some non GEO systems address this deficiency.

3. Boeing-Teledesic Constellation

The 288 LEO satellite constellation is designed to give high elevation everywhere.

Teledesic ; First 3 planes

Teledesic 24/plane
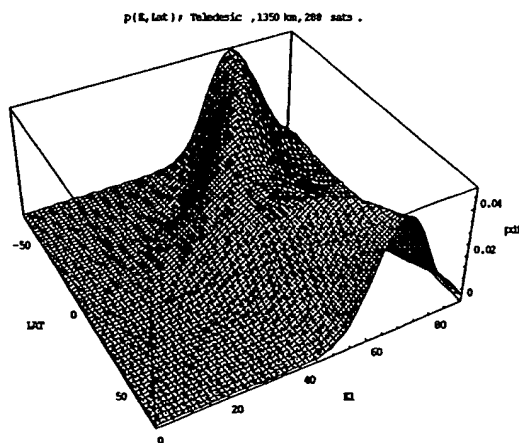
Fig. 3-1   First 3 Teledesic Planes

Fig. 3-2   Teledesic at Epoch   288 sats.
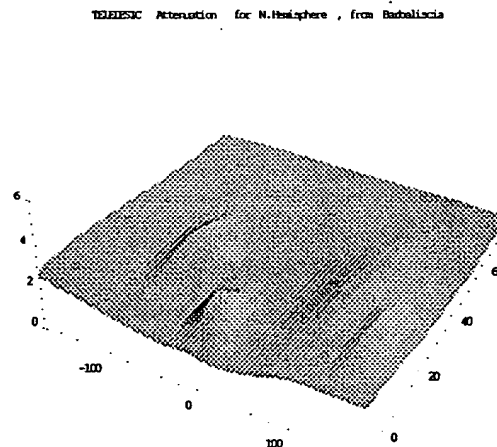
The Teledesic orbits are shown to scale in Figs. 3-1 and 2.   An altitude of 1350 km is combined with a near polar orbit of 98^0.   Each plane consists of 24 satellites, and the 12 planes are separated by 30^0 in Right Ascension.

Since the satellites present dynamic elevation angles to ground stations, intensive elevation angle searches in both time and area must be done to assess the Teledesic performance.   After these searches are done, an analytic form gives a close approximation to the elevation pdf.

Fig. 3-3 shows the pdf as a function of latitude(LAT).   Elevation angle is to the right, and LAT is coming out of the page.   The average elevation at high latitude nears 70^0.

p(E,Lat); Teledesic ,1350 km,288 sats .

TELEDESIC Attenuation for N.Hemisphere , from Bachaliscia
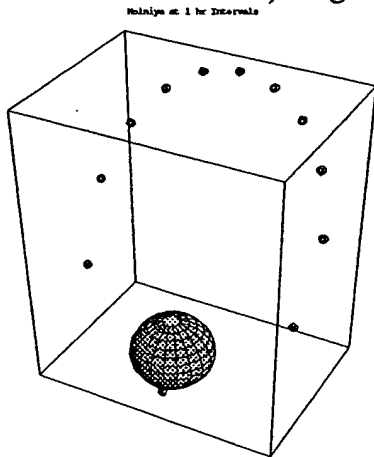
Fig. 3-3 Teledesic pdf vs LAT

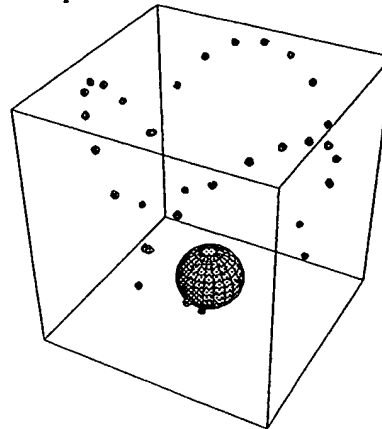**Fig. 3-4   Teledesic Attenuation   30GHz**

A nonlinear transformation is then performed on the pdf to find the average cosecant at each latitude. The result is then used to generate the characteristic Teledesic attenuation map of Fig. 3-4. The Teledesic attenuation is considerably lower than the GEO attenuation in the critical 25N to 70N temperate region.

4. MolniyaGEO System

In the mid 60s, the Soviets recognized another outstanding way to get good satellite coverage at high latitudes. They used an inclined elliptic satellite to get several hours of uninterrupted coverage at Moscow. (Actually, the history of the satellite would be fascinating, if at all known. They used a 63.4^0 inclination for stability, only a few years after the US physicist D.Blitzer studied the properties of orbits around the oblate earth and stable inclinations). Fig. 4-1 shows 1 hr snapshots of the 12 hour orbit.
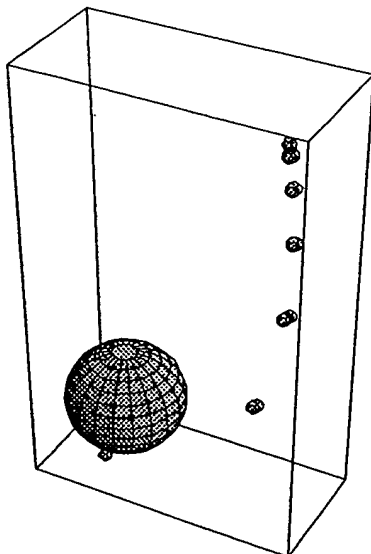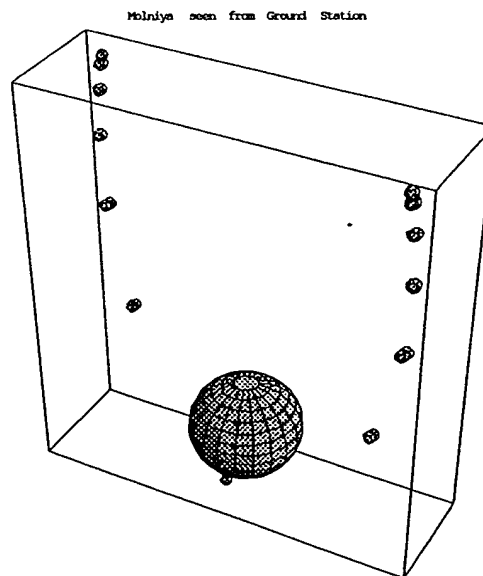

Fig. 4-1 Molniya 1 Hr Snapshots

Fig. 4-2 Three Phased Molniya

The Molniya orbits are even more useful for high latitude coverage than might be apparent from Fig. 4-1. Since the ground station on the earth is rotating with the earth, the Molniya appears quasi- stationary for several hours. The three phased Molniya of 4-2 allow continuous satellite visibility. From the ground station's perspective in a rotating coordinate system, the Molniya appear as
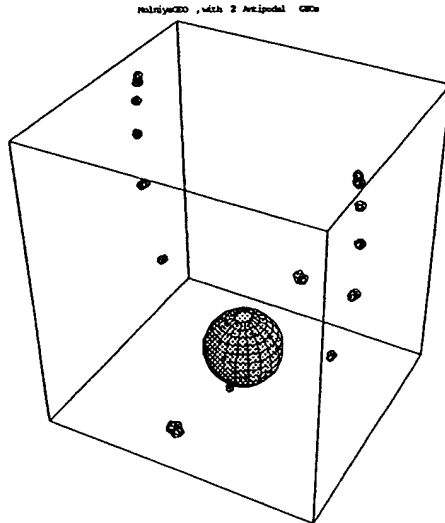

Fig 4-3 One Hr Snapshots of Ground View, One Molniya

Fig. 4-4 One Hr Snapshots of Ground View, Three Phased

Figs. 4-3 and 4 indicate that Molniya appears to be stationary for 4- 6 hours at each apogee, and a very useful communication satellite for 8 hours. How could the system designer assure high elevation throughout the Northern Hemisphere for all time? One obvious solution would be to include two antipodal GEOS, as seen on Fig. 4-5. For lack of a better name, it might be called a MolniyaGEO system.
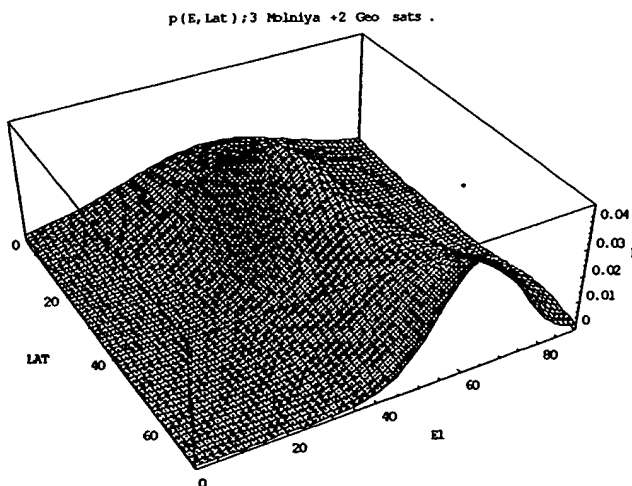
MolniyaGEO , with 2 Antipodal GEOs
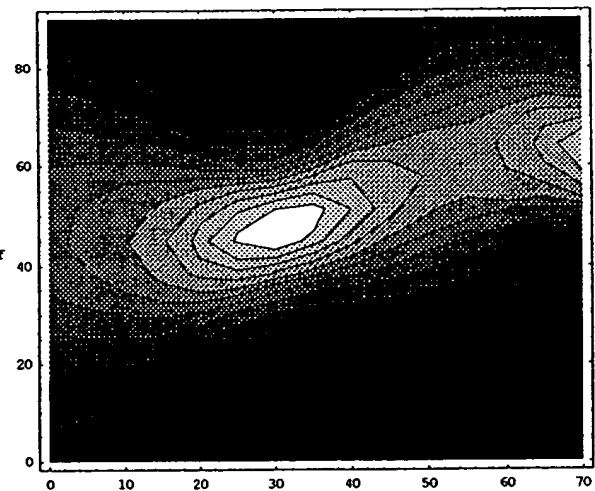
Fig. 4-5 MolniyaGEO System. With 3 Molniya, 2 GEO

Exhaustive elevation searches can be done for the MolniyaGEO system for all time and area. The elevation pdf has been found to be

MolniyaGEO pdf=

$$\frac{\left(5.22822\times10^{-6}\,LAT^4-0.000520006\,LAT^3+0.00512491\,LAT^2+0.165865\,LAT+x-47.0509\right)^2}{e^{-2\left(0.000029238\,LAT^4-0.00526509\,LAT^3+0.270942\,LAT^2-0.776901\,LAT+181.722\,e^{-\frac{LAT^2}{900}}-160.041\right)^2}}$$

$$|\,0.000029238\,LAT^4-0.00526509\,LAT^3+0.270942\,LAT^2-0.776901\,LAT+181.722\,e^{-\frac{LAT^2}{900}}-160.041|\quad \overline{2\pi}$$
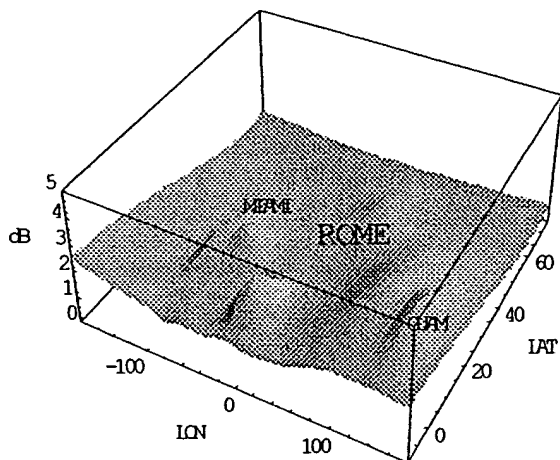
p(E,Lat);3 Molniya +2 Geo sats .

Fig. 4-6a MolniyaGEO pdf(El) v. LAT

Fig. 4-6b Contourplot of pdf(El)

Figures 4-6a and b show the Molniya pdf(elevation) from different viewpoints.
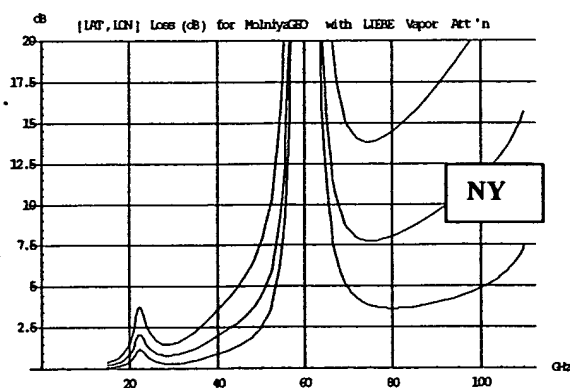
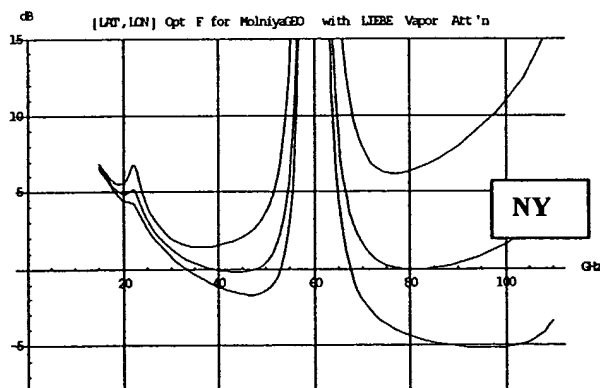**Fig. 4-7a MolniyaGEO Attenuation 30GHz**

Fig. 4-7b MolniyaGEO   45GHz

Attenuation maps can be generated as 4-7a and 4-7b for 30 and 45 GHz respectively. Attenuation is high in the tropics at 45 GHz, but moderate in the temperate zone for the MolniyaGEO constellation.   The average attenuation at a range of latitudes may be compared with 3 GEO (not shown), and distinctive advantages exist for the MolniyaGEO constellation at 45 GHz for the temperate region.

5. Optimum Communication Frequencies for MolniyaGEO

Some discussions of millimeter wave frequencies concentrate on the obvious higher losses at the higher frequencies.   Losses for a New York ground station as a function of frequency (middle curve, Fig.5-1) are seen to increase sharply with frequency.   The important air traffic routes at Iceland (bottom curve) show modest attenuation, and Rio de Janeiro (top) has disturbingly high attenuation.

Fig. 5-1 Loss(dB) at 3 Ground Sites v. F

Fig. 5-2 Net Loss at 3 Sites v. F
Loss+30-20Log(F)

In addition to loss, the system designer should be concerned with system costs. System costs are strongly related to antenna area. Maximum signal at minimum cost may be approached with a new variable called 'Net Loss', composed of (Loss-Gain at constant aperture). Fig. 5-2 shows net loss at constant antenna area. The positions of the minima are of interest, and the positions do not change as a function of antenna size and the constants in the net loss equation are chosen simply as a convenience for viewing. Local minima for NY appear at 44 GHz and 82 GHz, with 44 GHz being slightly preferable. In contrast, the global minimum for Iceland appears at 95 GHz. The sudden transition to the desirable 90 GHz region appears just north of New York. Worldwide plots of optimum frequencies for the 99% nonrainy condition may be shown as Fig. 5-3.
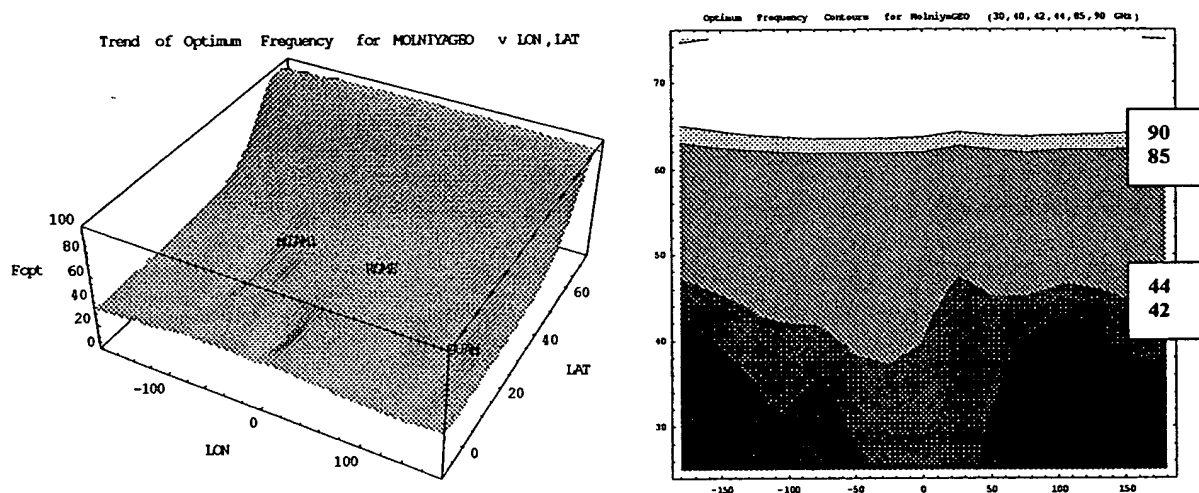

Fig. 5-3a Optimum MolniyaGEO Frequencies   Fig. 5-3b Optimum F Contours

The MolniyaGEO constellation suggests good opportunities throughout the Temperate Zone for the 40-46 GHz and the 90-100 GHz regions.   An equation for optimum frequency as a function of ground location is given in Appendix A.

We have seen that the Teledesic and MolniyaGEO systems offer such high elevation angles that frequencies much higher than 30 GHz appear attractive for VSATs and site diversity systems throughout much of the temperate region. The MolniyaGEO system was examined in detail, and systems with superior elevation statistics and a larger number of satellites such as Teledesic should be expected to be even more promising in the millimeter wave region.

6. Selected References

1.   F. Barbaliscia, M. Boumis, A. Martellucci, "World Wide Maps of Non Rainy Attenuation for Low-Margin Satcom Systems Operating in SHF/EHF Bands," Ka Band Conference, Sept. 1998.
2.   P. Christopher, "World Wide Millimeter Wave Attenuation Functions from Barbaliscia's 49/22 GHz Observations," Ka Band Conference, Taormina Sicily, Oct. 1999.
3.   A.K. Kamal, P. Christopher, "Communication at Millimeter Wavelengths," Proc. ICC, Denver, 1981.
4.   H.J. Liebe, P.W. Rosenkranz, G.A. Hufford, "Atmospheric 60 GHz Oxygen Spectrum: New Laboratory Measurements---," J. Quantum Spectroscopy and Radiative Transfer, Vol.48, 1992.

5. A.H. Jackson, P. Christopher, "A LEO Concept for Millimeter Wave Communication," Proc. IMSC, Ottawa, June, 1995.

6. P. Christopher, editor, **Millimeter Wave Satellite Communication**, Vol. 1, Satellite Orbits, Vol.2 Propagation and Attractive Frequencies, PFC Associates, Leesburg, VA, May 2000.
   A few copies are available at: pfchristop@aol.com

A Key Mathematical Background Reference:

7. S. Wolfram, **Mathematica A System for Doing Mathematics by Computer**, 3rd Edition, Wolfram Research, 1997.

Appendix A Attractive Frequencies for MolniyaGEO with Barbaliscia's 99% Nonrainy Condition

$$
\begin{aligned}
Opt.F(approx.) = {} & 51.3673\, e^{-\frac{1}{200}(LAT-70)^2} + 4.55605 + 187.652 \Big/ \Big(1.92203 \times 10^{-7}\, LAT^4 + 8.15535 \times 10^{-7}\, LAT^3 + \\
& 3.42574 \times 10^{-7}\, LON\, LAT^2 - 0.00187405\, LAT^2 + 1.15354 \times 10^{-8}\, LON^2\, LAT - 5.83206 \times 10^{-6}\, LON\, LAT + \\
& 0.000898808\, LAT + 1.48098\, e^{-\frac{1}{200}(LAT-10)^2 - \frac{1}{200}(LON-145)^2} + 2.03295\, e^{-\frac{1}{800}(LAT-18)^2 - \frac{(LON-102)^2}{1800}} + \\
& 1.1968\, e^{-\frac{1}{200}(LAT-52)^2 - \frac{1}{800}(LON-28)^2} - 2.78685\, e^{-\frac{LAT^2}{1800} - \frac{LON^2}{180000}} + 2.48024\, e^{-\frac{1}{72}(LAT-2)^2 - \frac{1}{200}(LON+7)^2} + \\
& 1.41803\, e^{-\frac{1}{50}(LAT-20)^2 - \frac{1}{200}(LON+60)^2} - 2.26449\, e^{-\frac{1}{200}(LAT+28)^2 - \frac{1}{200}(LON+77)^2} + 1.69839\, e^{-\frac{1}{200}(LAT-20)^2 - \frac{1}{128}(LON+82)^2} - \\
& 6.44437 \times 10^{-11}\, LON^4 - 3.5046 \times 10^{-8}\, LON^3 + 0.0000243378\, LON^2 - 0.000690105\, LON + 6.54566 \Big) - \\[6pt]
& 202.149 \Big/ \Big(1.92203 \times 10^{-7}\, LAT^4 + 8.15535 \times 10^{-7}\, LAT^3 + \\
& 3.42574 \times 10^{-7}\, LON\, LAT^2 - 0.00187405\, LAT^2 + 1.15354 \times 10^{-8}\, LON^2\, LAT - 5.83206 \times 10^{-6}\, LON\, LAT + \\
& 0.000898808\, LAT + 1.48098\, e^{-\frac{1}{200}(LAT-10)^2 - \frac{1}{200}(LON-145)^2} + 2.03295\, e^{-\frac{1}{800}(LAT-18)^2 - \frac{(LON-102)^2}{1800}} + \\
& 1.1968\, e^{-\frac{1}{200}(LAT-52)^2 - \frac{1}{800}(LON-28)^2} - 2.78685\, e^{-\frac{LAT^2}{1800} - \frac{LON^2}{180000}} + 2.48024\, e^{-\frac{1}{72}(LAT-2)^2 - \frac{1}{200}(LON+7)^2} + \\
& 1.41803\, e^{-\frac{1}{50}(LAT-20)^2 - \frac{1}{200}(LON+60)^2} - 2.26449\, e^{-\frac{1}{200}(LAT+28)^2 - \frac{1}{200}(LON+77)^2} + 1.69839\, e^{-\frac{1}{200}(LAT-20)^2 - \frac{1}{128}(LON+82)^2} - \\
& 6.44437 \times 10^{-11}\, LON^4 - 3.5046 \times 10^{-8}\, LON^3 + 0.0000243378\, LON^2 - 0.000690105\, LON + 6.54566 \Big)
\end{aligned}
$$

2